A-9001D

SENSING APPARATUS EMPLOYING VARIABLE COUPLER FIBEROPTIC SENSOR

S P E C I F I C A T I O N

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Application No. 09/316,143 filed May 21, 1999, which claims the benefit of U.S. Provisional Application Nos. 60/097,618 filed August 24, 1998, and 60/126,339 filed March 26, 1999; and this application further claims the benefit of U.S. Provisional Application No. 60/270,649 filed February 26, 2001. All of the aforementioned applications are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The present invention relates to improved designs for variable coupler fiberoptic sensors and to sensing apparatus using the improved sensor designs.

Variable coupler fiberoptic sensors conventionally employ so-called biconical fused tapered couplers. Such couplers are manufactured by a draw and fuse process in which a plurality of optical fibers are stretched (drawn) and fused together at high temperature. The plastic sheathing is first removed from each of the fibers to expose the portions for forming the fusion region. These portions are juxtaposed, usually intertwisted one to several twists, and then stretched while being maintained above their softening temperature in an electric furnace or the like.

As the exposed portions of the fibers are stretched, they fuse together to form a narrowed waist region—the fusion region—that is capable of coupling light between the fibers. During the stretching process, light is injected into an input end of one of the fibers and monitored at the output ends of each of the fibers to determine the coupling ratio. The coupling ratio changes with the length of the waist region, and the fibers are stretched until the desired coupling ratio is achieved—typically by a stretching amount at which the respective fiber light outputs are equal. The coupler is drawn to such an extent that, in the waist region, the core of each fiber is effectively lost and the cladding may reach a diameter near that of the former core. The cladding becomes a new "core," and the evanescent field of the propagating light is forced outside this new core, where it envelops both fibers simultaneously and produces the energy exchange between the fibers. A detailed description and analysis of the biconical fused tapered coupler has been given by J. Bures et al. in an article entitled "Analyse d'un coupleur Bidirectional a Fibres Optiques Monomodes Fusionnes", Applied Optics (Journal of the Optical Society of America), Vol. 22, No. 12, June 15, 1983, pp. 1918-1922.

Biconical fused tapered couplers have the advantageous property that the output ratio can be changed by bending the fusion region. Because the output ratio changes in accordance with the amount of bending, such couplers can be

used in virtually any sensing application involving motion that can be coupled to the fusion region.

Conventional variable coupler fiberoptic sensors have relied upon designs in which the fiberoptic coupler is pulled straight, secured under tension to a plastic support member and, in the resulting pre-tensioned linear (straight) form, encapsulated in an elastomeric material such as silicone rubber. The encapsulant forms a sensing membrane that can be deflected by external forces to cause bending of the coupler in the fusion region. The bending of the fusion region results in measurable changes in the output ratio of the coupler. The displacement of the membrane can be made sensitive to as little as one micron of movement with a range of several millimeters.

Fig. 1 of the accompanying drawings illustrates the basic principles of a sensing apparatus including a variable coupler fiberoptic sensor 10 as described above. In the form shown, the sensor 10 includes a 2 x 2 biconical fused tapered coupler 11 produced by drawing and fusing two optical fibers to form the waist or fusion region 13. Portions of the original fibers merging into one end of the fusion region become input fibers 12 of the sensor, whereas portions of the original fibers emerging from the opposite end of the fusion region become output fibers 14 of the sensor. Reference numbers 18 denote the optical fiber cores. The fusion region 13 is encapsulated in an

elastomeric medium 15, which constitutes the sensing membrane. The support member is not shown in Fig. 1.

In practice, one of the input fibers 12 is illuminated by a source of optical energy 16, which may be an LED or a semiconductor laser, for example. The optical energy is divided by the coupler 11 and coupled to output fibers 14 in a ratio that changes in accordance with the amount of bending of the fusion region as a result of external force exerted on the sensing membrane. The changes in the division of optical energy between output fibers 14 may be measured by two photodetectors 17 which provide electrical inputs to a differential amplifier 19. Thus, the output signal of differential amplifier 19 is representative of the force exerted upon medium 15. It will be appreciated that if only one of the input fibers 12 is used to introduce light into the sensor, the other input fiber may be cut short. Alternatively, it may be retained as a backup in the event of a failure of the primary input fiber. It should be noted that, for simplicity, the coupler 11 is shown without the aforementioned fiber twisting in the fusion region. Such twisting is ordinarily preferred, however, to reduce lead sensitivity, which refers to changing of the output light division in response to movement of the input fiber(s).

Because variable coupler fiberoptic sensors can be made entirely from dielectric materials and optically coupled to remote electronics, they are particularly advantageous for

applications in which the presence of electrically conductive elements at the sensor location would pose the risk of electrical shock, burns, fire, or explosion. In the medical field, for example, variable coupler fiberoptic sensors have been proposed for monitoring patient heartbeat during MRI examinations. See U.S. Patent 5,074,309 to Gerdt, which discloses the use of such sensors for monitoring cardiovascular sounds including both audible and sub-audible sounds from the heart, pulse, and circulatory system of a patient. The use of sensing devices having metallic components in an MRI environment has been known to cause severe burning of patients due to the presence of strong radio frequency fields.

Other applications of variable coupler fiberoptic sensors can be found in U.S. Patent 4,634,858 to Gerdt et al. (disclosing application to accelerometers), U.S. Patent 5,671,191 to Gerdt (disclosing application to hydrophones), and elsewhere in the art.

As compared with other types of fiberoptic sensors, the described variable coupler sensors offer a uniquely advantageous combination of low cost, relatively simple construction, high performance (e.g., high sensitivity and wide dynamic range), and versatility of application. Other known fiberoptic sensors have used such principles as microbending loss, light phase interference, and polarization rotation by means of birefringence. Fiberoptic micro-bending sensors are designed to sense pressure by

excluding light from the fiber in proportion to the changes in pressure. The output light intensity decreases with increases in measured pressure, as pressure is transduced into light loss. Because the measurement accuracy is reduced at lower light levels, the dynamic range of such sensors is severely limited. Interferometric fiberoptic sensors measure changes in pressure by applying pressure to an optical fiber to change its index of refraction. This results in a phase delay that is measured by utilizing a Mach-Zehnder or Michaelson interferometer configuration. These sensors are extremely expensive and require sophisticated modulation techniques that render them unsuitable for many applications. Polarization varying fiberoptic sensors alter the polarization state of a polarized optical signal in accordance with a change in temperature or pressure. Such polarized light sensors require special optical fiber and expensive polarizing beam splitters.

Despite their advantages, variable coupler fiberoptic sensors have been subject to certain limitations inherent in the conventional pre-tensioned linear (straight) coupler design. The conventional design imposes, among other things, significant geometrical limitations. In particular, the size of the sensor must be sufficient to accommodate the fiberoptic leads at both ends of the sensor. The fiberoptic lead arrangement also requires the presence of a clear space around both ends of the sensor in use.

Especially in medical applications, such as when placing a sensor on a patient's body for continuous monitoring, the size and lead positions of the sensor are both important issues. Another limitation results from the fact that any displacement of the fusion region necessarily places it under increased tension. At some point of displacement, the tension in the fusion region will become excessive, causing the fusion region to crack or break, with resulting failure of the coupler.

SUMMARY OF THE INVENTION

The present invention provides new variable coupler fiberoptic sensor designs that have comparatively little or no susceptibility to the above described over-tensioning of the fusion region. More particularly, in contrast to the conventional pre-tensioned linear coupler used in prior sensor designs, the present invention utilizes a coupler arrangement that permits deflection of the fusion region without accompanying tension. The coupler may be arranged to have a curved form, for example, which in the most preferred embodiments is substantially U-shaped. By arranging the coupler in a substantially U-shaped form, it also becomes possible to locate the fiberoptic leads adjacent to each other rather than at opposite ends of the sensor, thus avoiding the earlier discussed geometrical limitations inherent in the conventional pre-tensioned linear coupler design.

The present invention also retains the basic advantages of conventional variable coupler fiberoptic sensors relative to other types of fiberoptic sensors and sensors requiring electrically conductive elements at the point of use. Indeed, sensors designed in accordance with the invention may be used to advantage in any application that has heretofore employed conventional variable fiberoptic coupler sensors.

Thus, in one of its various aspects, the present invention provides a fiberoptic sensing apparatus comprising a fiberoptic coupler in which a plurality of optical fibers are joined through a fused coupling region. The optical fibers include at least one input optical fiber and a plurality of output optical fibers, the fiberoptic coupler distributing light incident to the input optical fiber among the plurality of output optical fibers. The apparatus further comprises a support member, and the coupler is mounted to the support member and configured such that at least a portion of the fused coupling region can be deflected without putting the fused coupling region under tension.

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to the input optical fiber among the plurality of output optical fibers. The apparatus further comprises a support member, and the coupler is mounted to the support member and configured such that the fused coupling region has substantially a U-shape.

Other aspects of the invention will become apparent from a reading of the following description of the preferred embodiments with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates the basic construction of a conventional variable coupler fiberoptic sensor.

Fig. 2 is a top view of a variable coupler fiberoptic sensor according to the invention, being designed for monitoring cardiovascular sounds such as from the wrist or the chest.

Fig. 3 is a sectional side view of the sensor of Fig. 2.

Fig. 4 shows explanatory views (Views 4a - 4d) of normal and deflected states of the fusion region of a conventional pre-tensioned linear coupler.

Fig. 5 shows corresponding explanatory views (Views 5a - 5d) for a U-shaped fusion region in accordance with the principles of the invention.

Fig. 6 shows a fiberoptic wrist sensing apparatus according to the invention.

Fig. 7 is a graph depicting the response of the wrist sensor in the apparatus of Fig. 6 to pulsations of the wrist.

Fig. 8 is another graph of the sensor response at the wrist.

Fig. 9 is an exploded view of another wrist sensor according to the invention.

Fig. 10 is an end view of the Fig. 9 sensor in assembled form.

Fig. 11 illustrates another wrist sensor according to the invention, shown in section as worn on the wrist.

Fig. 12 is a perspective view of a carotid artery sensor according to the invention.

Fig. 13 is a fragmentary side elevation of the Fig. 12 sensor.

Fig. 14 is a perspective view showing the Fig. 12 sensor and its fiberoptic leads with installed connectors.

Fig. 15 shows another embodiment of the invention in which a variable coupler fiberoptic sensor is coupled to a remotely tethered bladder via a fluid column.

Fig. 16 is a side view of the bladder in Fig. 15.

Fig. 17 is a close-up view showing the arrangement of the fiberoptic sensor and an associated sensor diaphragm in Fig. 15.

Fig. 18 shows a sensing pad apparatus incorporating the embodiment of Figs. 15-17.

Figs. 19-21 show output signals obtained using the apparatus of Fig. 18 to monitor heartbeat and breathing of an adult male.

Fig. 22-25 show a more practical arrangement of the sensor and associated diaphragm, laser light source, and electronics for the embodiment of Figs. 15-17.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figs. 2 and 3 of the accompanying drawings show an example of a variable coupler fiberoptic sensor 20 in accordance with the invention. The sensor is constructed for placement against a medical patient's body, such as on the chest or wrist, for sensing cardiovascular sounds including both audible and sub-audible sounds from the heart, pulse, and circulatory system.

The sensor 20 comprises a support member 22 having a generally circular head portion 24, which is provided with a central well or through hole 26, and a handle-like extension 28. A biconical fused tapered coupler 30 is mounted to the support member with at least a portion (here, the entirety) of its fused coupling region 32 disposed in the space 26 and arranged in a U-shape. Input fiber leads 34 and output fiber leads 36 of the coupler are disposed beside one another in a channel 29 formed in the extension 28. The leads are manipulated so as to bend the coupling region 32 through 180° into the desired shape and then secured within the channel by a suitable adhesive, such as an epoxy-based

glue. The coupling region, which is not under tension, may be potted by filling the space 26 with elastomer to form a sensing membrane 38 (not shown in Fig. 2) in the known manner—for example, by filling with a silicone rubber such as GE RTV 12. Alternatively, as will be seen hereinafter, the coupling region may be coated with a layer of coating material such as GE SS 4004 (polydimethylsiloxane with methyl silsesquioxanes) to eliminate the need for potting. This material is normally used as a primer for bonding room temperature vulcanizing (RTV) materials to surfaces that would otherwise form weak bonds. The advantage of eliminating the potting is that the sensitivity is increased, because the potting tends to reduce sensitivity no matter how thinly it is applied. Support member 22 is suitably formed of a moldable plastic, such as Plexiglass®, polyvinyl chloride (PVC), or other suitable materials known in the art.

As shown in Fig. 3, the upper portion of the membrane 38 has a convex surface 39 that protrudes from the plane of the support structure for contacting the patient's body. The convex configuration of the contact surface makes the sensor more of a point probe to better localize the cardiovascular sounds being monitored. In a practical embodiment of the sensor, the maximum diameter of the membrane may be about the same as that of a nickel with the contact surface protruding by about half that amount, but the membrane may be smaller or larger as desired to suit a

particular application. The support plate dimensions may be any convenient size, so long as the coupler fusion region and the fiber portions near the fusion region are securely supported. The sensitivity of the device is dependent upon the stiffness of the membrane, as in prior devices. Using softer or stiffer membrane materials will provide different sensitivities to the readings received from the body coupling.

When the contact surface 39 is placed upon a patient's body, as at the chest or wrist, the membrane 38 couples skin displacements associated with cardiovascular sounds to the coupling region 32 of the fiberoptic coupler 30. The coupling region is thereby deflected, changing the light output ratio of the output fibers 36 in accordance with the sounds being monitored.

Figs. 4 and 5 provide a pictorial comparison between the deflection of a conventional pre-tensioned linear fiberoptic coupler and the deflection of the U-shaped coupler in the sensor of Figs. 2 and 3. Views 4a and 4c are top and side views, respectively, showing the fusion region of the conventional coupler in its normal state. Views 4b and 4d are corresponding views of the fusion region being deflected by a downward force F. Views 5a - 5d in Fig. 5 are corresponding views to Fig. 4, but show the U-shaped coupler employed in the present invention.

As will be appreciated from View 4d, the deflection of the fusion region in the conventional coupler causes a

bowing that tends to stretch and thereby increase the tension on the fusion region. By contrast, the deflection of the U-shaped fusion region in View 5d, which is seen to occur along a direction perpendicular to the plane of the U-shape, merely causes a flexing of the U along its height (horizontal dimension in View 5d), without subjecting the fusion region to tension. Thus, even large displacements of the fusion region will not cause cracking or breaking.

In the practice of the present invention, the fusion region of the fiberoptic coupler need not be U-shaped or even substantially so. Any configuration of the fusion region that allows for deflection without tensioning of the fusion region may be used. For example, arcuate shapes, parabolic and hyperbolic shapes with widely divergent sides, and other curved shapes may be used. A substantially U-shaped form may be preferred, however, because such a form allows positioning of the coupler input and output leads on the same side of the sensor, resulting in a compact design that does not require clearances to accommodate leads at opposite ends of the structure. A substantially U-shaped form also produces significant increases in sensitivity, linearity, and dynamic range as compared with the conventional linear couplers. Other shapes, such as those mentioned above, may also produce these advantages. The length of the fusion region may be established during production as previously explained, and in actual sensors

constructed in accordance with the invention has typically been about 1.5 cm.

Fig. 6 shows another variable coupler fiberoptic sensor 20′ in accordance with the invention. The sensor has the same basic structure as that of the previous embodiment, except that the support member 22′ is formed as a substantially rectangular plate angled at about 30° to conform to the human wrist anatomy and facilitate wearing of the sensor by the patient, as by strapping the sensor to the wrist. As also shown in Fig. 6, one of the input leads 34 is optically coupled to a light source 40 (e.g., and LED or semiconductor laser) and the output fibers 36 are optically coupled to a photodetection/differential amplifier circuit 42, as previously described in connection with Fig. 1. The differential amplifier circuit may be coupled to an oscilloscope 44 or some other form of display device, such as a personal computer, to display the output of the differential amplifier circuit. If appropriate to a particular application, the support member may house the light source 40, the differential amplifier circuit 42, and a radio transmitting device (not shown) coupled to the differential amplifier circuit to provide for remote monitoring. Indeed, such provision can be made in any of the sensor structures of the invention described herein.

Fig. 7 shows the wrist heartbeat/breathing signal obtained from a human subject with the sensor 20′ of Fig. 6. The data stream in Fig. 7 was obtained at a sampling rate of

128 samples per second. It will be appreciated that the pulse waveform, as read by the sensor, is a more complex phenomenon than standard pulse readings. The pulse waveform exhibits the amplitude structure of the pulse as a function of time. The amplitude structure of the pulse is not what is "felt" as an impulse function by a finger at a pulse point, although that function is present. Within the amplitude structure, there are all of the heart sounds as well as information on breathing and other indicators of physical condition. The sensitivity achieved with sensors according to the present invention makes them very good at sensing the complex pulse waveform.

Fig. 8 shows another wrist heartbeat/breathing signal obtained from a human subject with the sensor 20'. Here, the data stream was digitized using a 12-bit A/D converter at a sampling rate of 64 samples per second. The heartbeat signal is very well resolved, as the inset graph demonstrates. In addition, the modulation introduced by the breathing cycle is clearly visible over the course of the 84 second run.

Figs. 9 and 10 show another embodiment of the invention, applied to a wrist sensor 50. In this embodiment, the fusion region 62 of the fiberoptic coupler is not potted, but coated as previously discussed in connection with Fig. 1. The fusion region 62 is coupled to pulsations of the wrist (denoted by arrow P) by a fluid- or gel-filled elastic pillow 68. The fiberoptic coupler is

mounted to a support plate 52 similar to that of Fig. 6, except that the support plate 52 is planar, not angled (the channel for the input and output leads 64, 66 having been omitted from illustration for simplicity). The support plate is secured to the top side of pillow 68 and a cover 69 is attached to the top side of the support plate to protect the fusion region 62 of the coupler 60 at the hole 56. The hole 56 allows the hydraulic pressure of the pulse activity to push on and deflect the fusion region by virtue of the contact between the fusion region and the upper surface of the pillow 68 which, due to its flexibility, protrudes into the hole 56 to contact the coupler fusion region. A wrist strap 57 attached to the support plate 52, as by glue, allows the sensor to be secured to the wrist. Reference numbers 64 and 66 denote the input fibers and output fibers, respectively.

The unpotted sensor design of Figs. 9 and 10 is advantageous over the potted designs previously described, because the absence of the sensing membrane results in greater sensitivity. Also, unlike the bent design in Fig. 6, the planar configuration of the support plate does not require out-of-plane bending of the coupler leads, which causes a reduction of light intensity. Instead, the coupler is maintained in a planar configuration, which optimizes the light intensity in the system.

Fig. 11 shows still another embodiment of the invention, applied to a wrist sensor 70 shown in cross-

section as worn on the wrist. The sensor includes a frame member 72 having an inner configuration which conforms generally to the wrist, as shown. The frame member may be constructed from any suitable material, preferably a plastic such as Delrin®, PVC, acrylic, Lucite®, Plexiglass®, styrene, or other polymers.

An upper portion of the frame provides a chamber 77 for housing the fiberoptic coupler 80 and its support plate 81. Since the coupler is housed by the frame member, the support plate, which is channeled to receive the input and output leads, need not include an opening (e.g., a well or through hole) to house the fusion region 82 of the coupler as in previous embodiments. The fusion region is coated, rather than potted, as previously described. The support plate 81, which may be of the same material as the frame 72, and the coupler are assembled as a module and glued in place in the chamber 77. The chamber is closed by a protective cover plate (not shown).

To couple the fusion region to the pulsations of the radial artery, a fluid column 74 is provided. The column has a pair of resilient membranes 73 and 75 provided at its inner and outer ends, respectively, and extends through the thickness of the frame 72 between the chamber 73 and the frame inner surface. The coupler module is installed with the coupler fusion region 82 in contact with the outer membrane 75 of the fluid column. The outer membrane is attached to an annular boss 76 to raise the height of the

fluid column for contact with the coupler fusion region. The contact with the outer membrane may subject the fusion region to a slight pre-load. The coupler may be manufactured such that the pre-loading of the fusion region will produce a substantially equal division of light between the output fibers, thus providing a more linear dynamic range. The inner portion (lower portion in Fig. 11) of the fluid column is stepped as shown, so as to increase the diameter of the coupling area at the wrist.

The membranes constitute an important part of the fluid column. Since the arterial pulsations are weak, the membranes should be light, thin, and of low durometer and high extensibility for optimum performance. At the same time, at least the inner membrane should be rugged enough to endure continuous contact with the skin. A material found to have excellent characteristics for the membrane is FlexChem, an FDA-approved, highly durable, vinyl based material available in pellet form from Colorite. FlexChem is also thermo-moldable, which permits the inner sensing membrane 73 to be molded to provide maximum coupling area with the radial artery and to protrude from the inner surface of the frame member 72 for better coupling with the wrist. A compatible fluid for use with FlexChem membranes is medical grade MDM silicone fluid available from Applied Silicone Corp. Water, incidentally, is not preferred for use with FlexChem membranes since the membranes are permeable to water vapor.

Several inner membrane sizes were tested to determine the effect on sensor response. In particular, membrane diameters of 4 mm, 7 mm, and 10 mm were tested for response to driven-oscillator stimuli calibrated using a commercial accelerometer. The response was examined over a frequency range of 0 to about 11 Hz (cardiovascular and breathing signals are typically in the range from 0.1 to 4 Hz). Each of the membranes provided acceptable response, with the 10 mm membrane providing the best response.

Returning to Fig. 11, the present embodiment also demonstrates how ancillary components, such as the light source and output circuitry (e.g., photodetectors and differential amplifier circuitry) may be incorporated into the sensor unit. More particularly, such components may be housed in one (as shown) or more internal chambers 79 of the frame 72.

Figs. 12 - 14 illustrate another embodiment of the invention, applied to a sensor 80 for the carotid artery. This sensor uses a planar, channeled support plate 82 and coupler arrangement similar to that of Fig. 9, except that the fusion region is potted to provide a sensor membrane. The membrane area may be made sufficiently large (e.g., about the size of a quarter dollar) to allow for the addition of a spherical cap 99' over the convexly protruding surface of the sensing membrane 98. The addition of the spherical cap renders the sensor less sensitive to any rocking motion caused by the hand when the sensor is

manually pressed against the neck. The coupler is protected at the back side (bottom in Figs. 12 and 13) of the sensor by a plastic cover plate 97. The sensor may be secured to the neck by any suitable means, such as adhesive tape.

The input and output fibers are encased as pairs in respective protective sheaths 102 and 104, which in turn are encased in an outer protective sheath 106. Fiberoptic connectors 108 are provided at the ends of the leads to interface the sensor with external components.

Figs. 15-17 show an additional embodiment of the invention in which the fiberoptic coupler is coupled to external motion through a fluid column. In this embodiment, the fluid column is in the form of an air-filled hose 200 (connecting hose), although other fluids, liquid or gasseous, could be used. The fluid column is terminated at one end by an expandable bladder 202, and its other end by a sensor diaphragm 204. The bladder make take any suitable form as long as it is effective to couple the external movement (e.g., of a human subject) to the sensor diaphragm via the fluid within the connecting hose. In one example, the bladder was constructed by attaching a ten-durometer silicone rubber sheet 205 with a thickness of 0.010 inch to the perimeter of a substantially rigid plastic disk 206 (Fig. 16). The sensor diaphragm was constructed by stretching and securing a portion of the same ten-durometer silicone rubber over one end of a rigid tubular member 208, specifically 1/2 inch copper tubing (Fig. 17). The bladder

and the connecting hose are filled with air to expand the bladder and the sensing diaphragm by manual operation of a conventional sphygmomanometer bulb assembly 210 (bulb, one-way valve, and cut-off valve), which is connected to a "T" connector 212, the other two branches of which are connected, respectively, to the bladder and the sensor diaphragm via the connecting hose.

The fiberoptic coupler is mounted to a support plate 214 with the fusion region 216 of the coupler in contact with the sensor diaphragm in essentially the same manner as in the embodiment of Fig. 11. In the present embodiment, which is a laboratory prototype, the sensor support plate is mounted to a bracket 218, as by gluing, which is in turn adjustably mounted to a conventional magnetically actuated support post 220 device on a metal table 222.

An advantage of the arrangement of the present embodiment is that the use of an inflatable bladder allows the fiberoptic sensor and its associated leads, light source, and electronics to be conveniently housed or otherwise arranged remotely from the external movement source to be monitored (e.g., a human or animal subject), and only the inflatable bladder and a portion of the connecting hose need be placed in the vicinity of the movement source.

Fig. 18 illustrates how the embodiment just described may be incorporated in a sensing pad arrangement to monitor an object for purposes as described in our co-pending

International Application No. PCT/US99/19259 (Publication No. WO 00/10447), which is incorporated herein by reference. The arrangement shown in Fig. 18 includes a pad 230 supported on a cot 231 and having a recessed or cut-out portion 232 that accommodates the bladder and a portion of the hose. This allows the bladder, when inflated, to protrude above the surface of the pad by an amount sufficient to contact the body of a subject resting on the pad and thereby couple movement of the subject to the coupling region of the fiberoptic sensor via the fluid column and the sensing diaphragm, but without causing the subject a sense of discomfort as if lying on a lump or the like. It is also possible to provide the bladder as an integral part of the pad and to provide a connector on the pad to connect the bladder to the connecting hose.

Figs. 19-21 show output signals for the breathing patterns of an adult male lying on his back on the pad and cot shown in Fig. 18.

Figs. 22-25 illustrate how the fiberoptic coupler and the associated sensing diaphragm and electronics may be arranged in a more practical manner within a housing 300 having a door 301. In addition to showing a more practical packaging arrangement, it will be seen that the fiberoptic sensor mount 302 includes a backing plate or mechanical stop 303 to prevent overstressing the fiberoptic sensing element in the event of excessive expansion of the diaphragm 304 due to over inflation. Of course, one or more pressure

regulators may be included to regulate the inflation pressure on the sensor diaphragm and/or the bladder.

It should be noted that the optical fiber used in the sensors of the present invention is most preferably of very high quality, such as Corning SMF28 which exhibits an optical loss of about 0.18 dB per Km. The photodetectors may be gallium-aluminum-arsenide or germanium detectors for light wavelengths above 900 nm and silicon detectors for shorter wavelengths.

The photodetectors may be connected in either a photovoltaic mode or a photoconductive mode. In the photovoltaic mode, transimpedance amplifiers (which convert current to voltage) may be used to couple the detectors to the differential amplifier inputs. The transimpedance amplifier outputs may also be filtered to eliminate broadband noise. As another example, the transimpedance amplifier outputs could be fed directly to a digital signal processor (DSP), where subsequent filtering and processing could be accomplished digitally through programmed algorithms. A DSP having transimpedance inputs would, of course, eliminate the need for discrete transimpedance amplifiers in the preceding example. In the photoconductive mode, the detector outputs can be connected to a conventional voltage amplifier. This approach results in more noise, but may be used in applications where cost is a major concern and a lower noise level is not.

It is to be understood, of course, that the foregoing embodiments of the invention are merely illustrative and that numerous variations of the invention are possible in keeping with the invention as more broadly described herein.